An investigation of flexible $Cu(In,Ga)Se_2$ solar cells under low intensity low temperature for potential application for outer planetary missions

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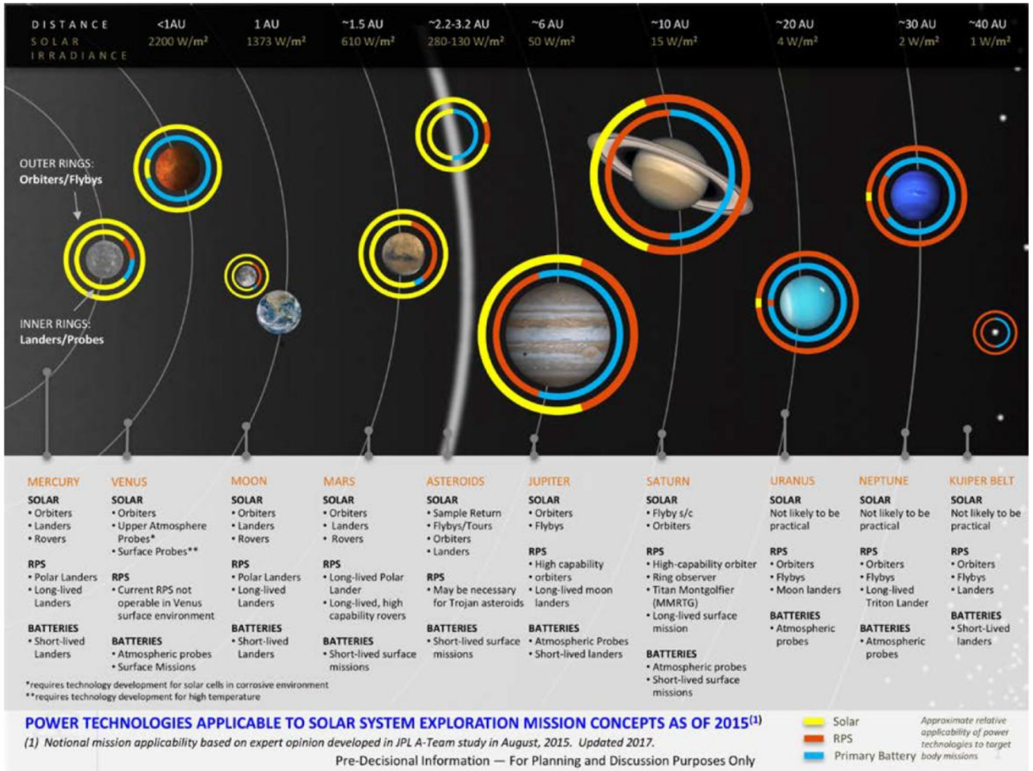
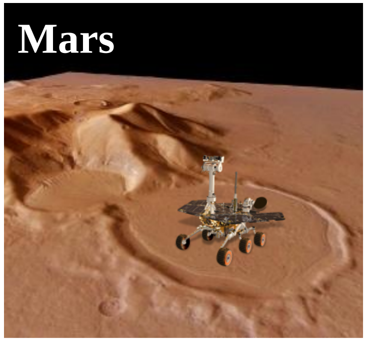
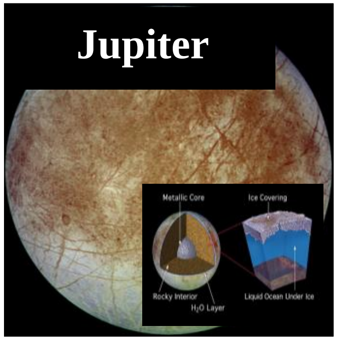
Photovoltaics for Next Generation Space Missions: Deep Space/Outer Planetary Missions



- NASA
- ESA
- JAXA
- Space X





- Higher power requirements for outer planet exploration
  - Beyond power for most radioisotope thermoelectric generators (RTG)

- Outer planets have low temperature compared to Low Earth Orbit (LEO) and some missions, like those near Jupiter, will encounter intense radiation belts.

- Flexible radiation hard thin films solar cells may be competitive if packing ratio/specific power is high compared to multijunction
  - <u>Particularly for low cost satellites</u> (CubeSat and SmallSat, 6U and 24U)

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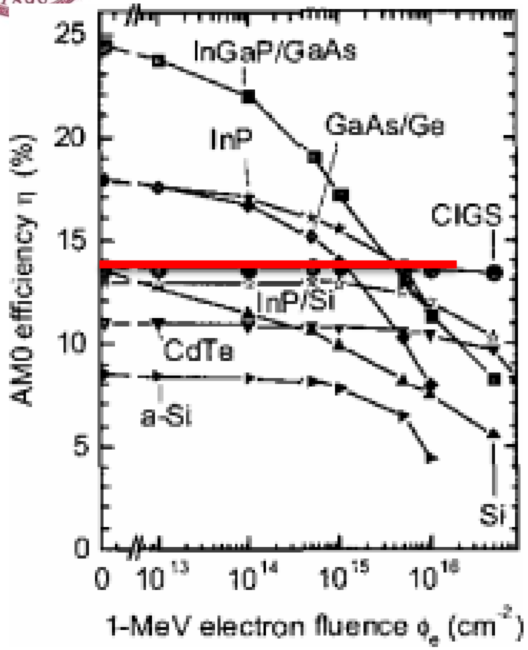
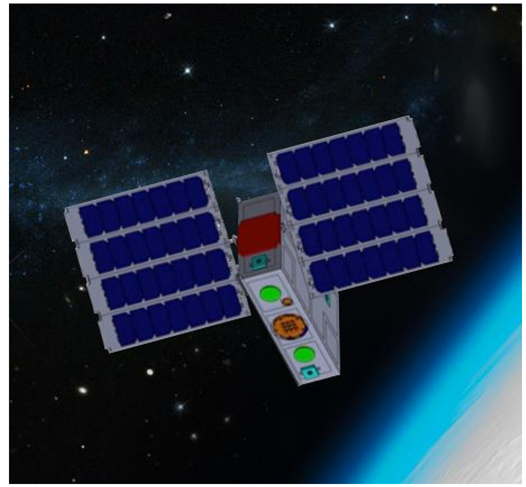
CIGS for Deep Space: a *unique application*



A. Jasenek *et al.*, Proc. WCPEC-3, 2003.



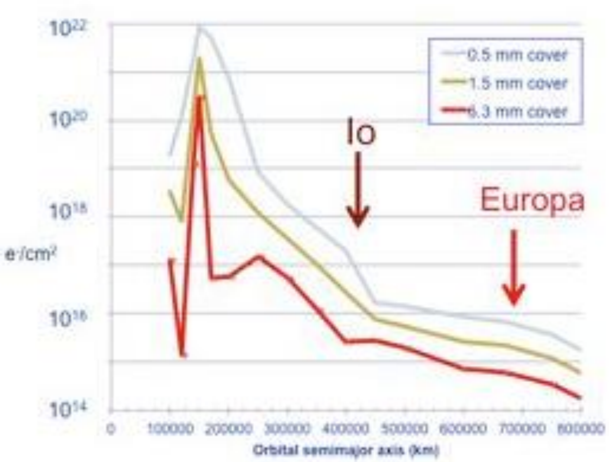
www.nasa.gov/mission_pages/smallsats

BioSentinel - www.nasa.gov

	I (AM0 suns)	I (W/m^2)	T_{eq} (K)
Saturn	0.011	14.82	100
Jupiter	0.037	50.26	135
Mars	0.431	586.2	263

Performance	NRA Goal
LILT BOL cell efficiency	35%
LILT EOL cell efficiency	28%
LILT EOL array specific power	8-10 W/kg
1AU BOL packaging density	60 kW/m^3
Stowed & launch capability	Yes
Operation in 100-300V range	Yes
Plasma operation 2eV, 1e8/cm^3	Yes
LILT EOL minimum array power	5 kW

JPL (NASA) EESP Base Report 4/26/2017: "Solar Arrays for LILT and High Radiation Environments."



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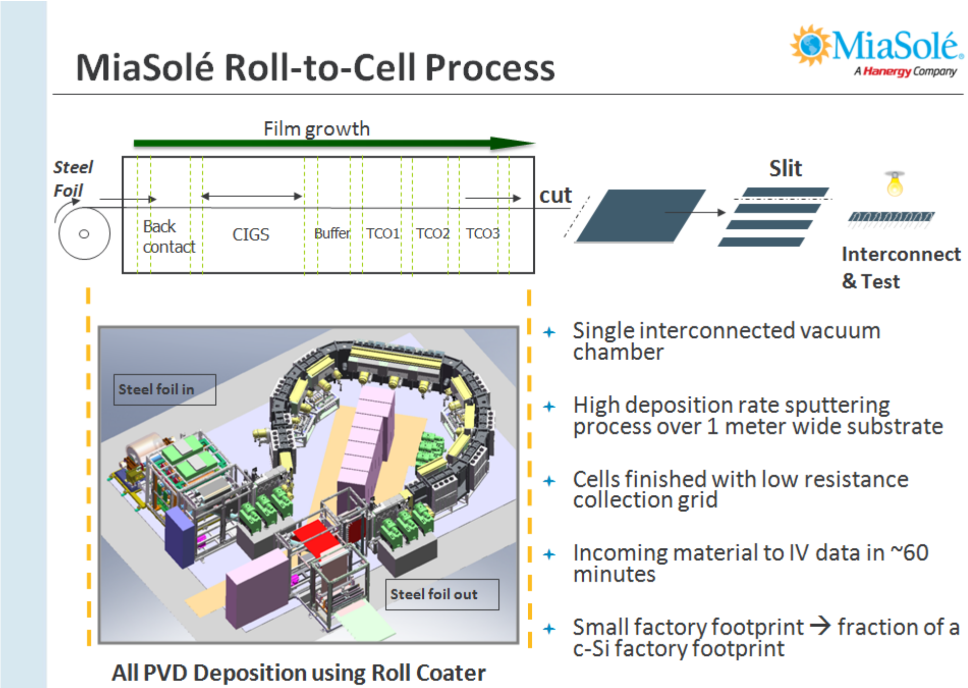
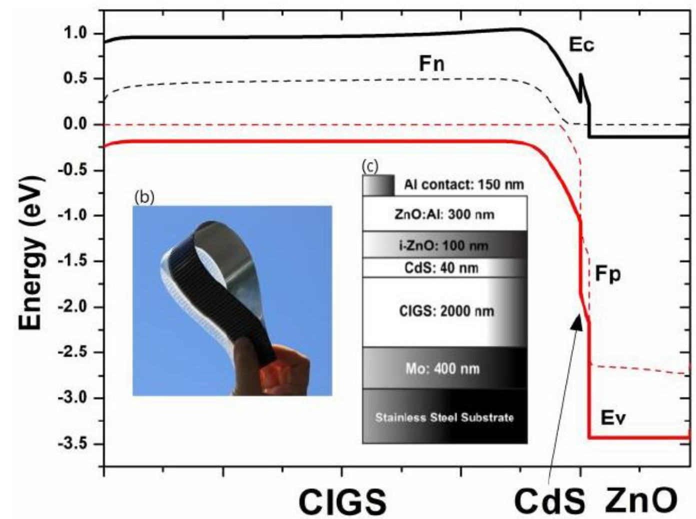
- Low cost, deployable technology
- (At least) equivalent payload
- Higher packing volume
- Radiation hard

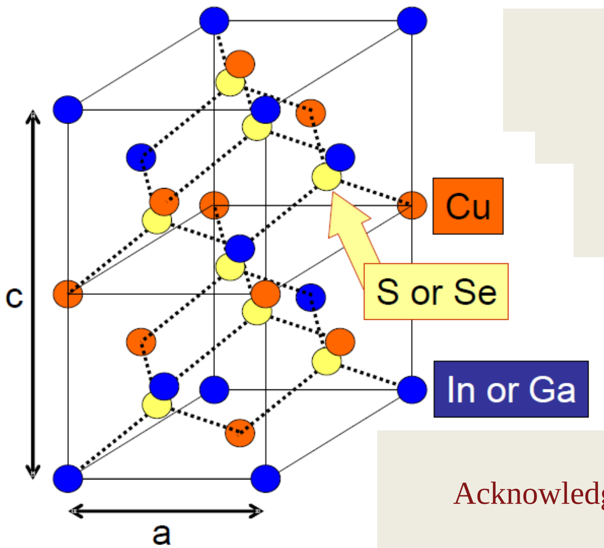
Flexible (commercial) CIGS: *MiaSolé product*

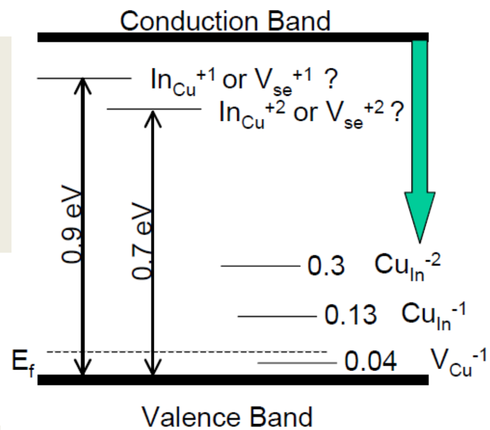




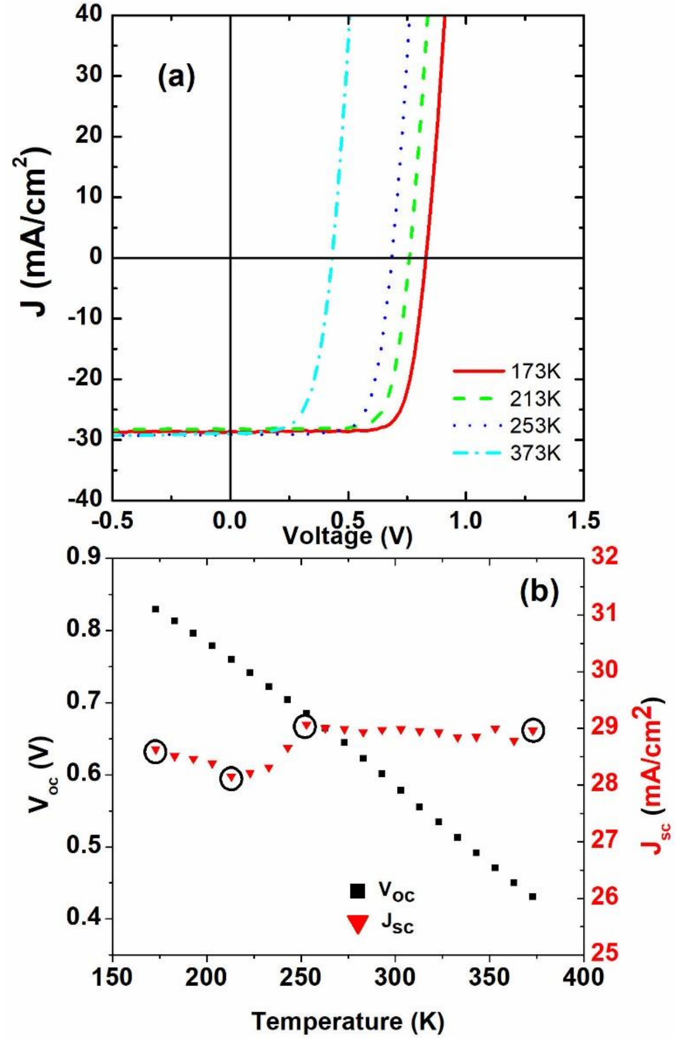
- Commercial grade CIGS with module efficiency of 17 % (20% - 2020)
- PVD Roll-to-Cell process on flexible steel
- Specifications: (for example - *FLEX-03WS*) 1.6 Kg/m^2
- 1293 mm x 1010 mm = 190 W
- Payload/Specific Power (AM1.5G) ~ 90 W/kg

CIGS: Materials Properties: *Metastability*





Acknowledgement - Angus Rockett (CSM)



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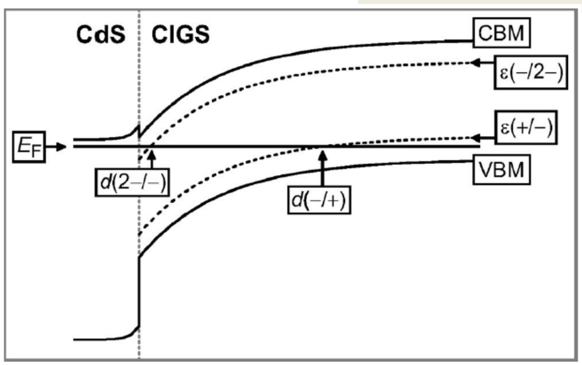
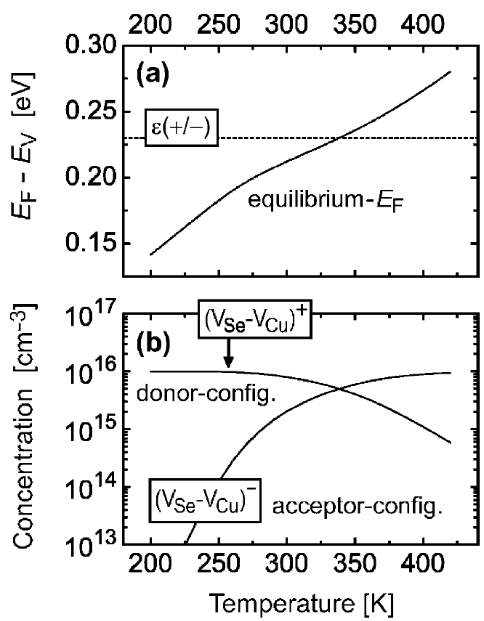
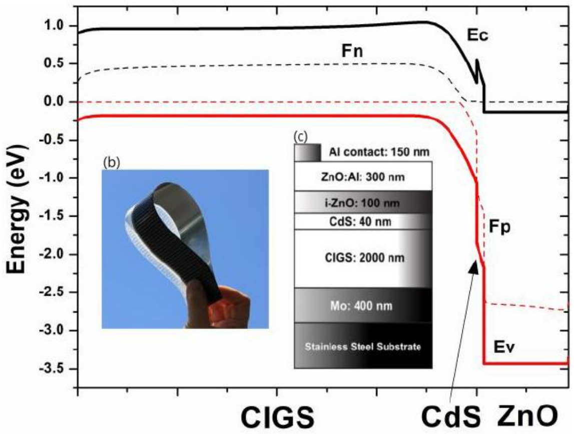


S. Lany and A. Zunger, Journal of Applied Physics **100** (11), 113725 (2006).



Reversible metastability under PV operating conditions

Effects of Metastability: *LILT Effect*



- *Relaxed – dark 330 K for 1 hour*
- *Metastable – light soaked at RT for 1 hour (AM0)*

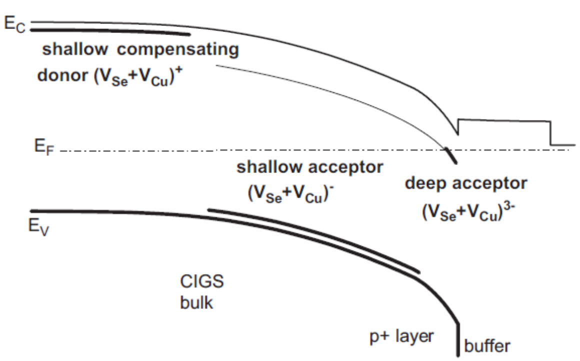
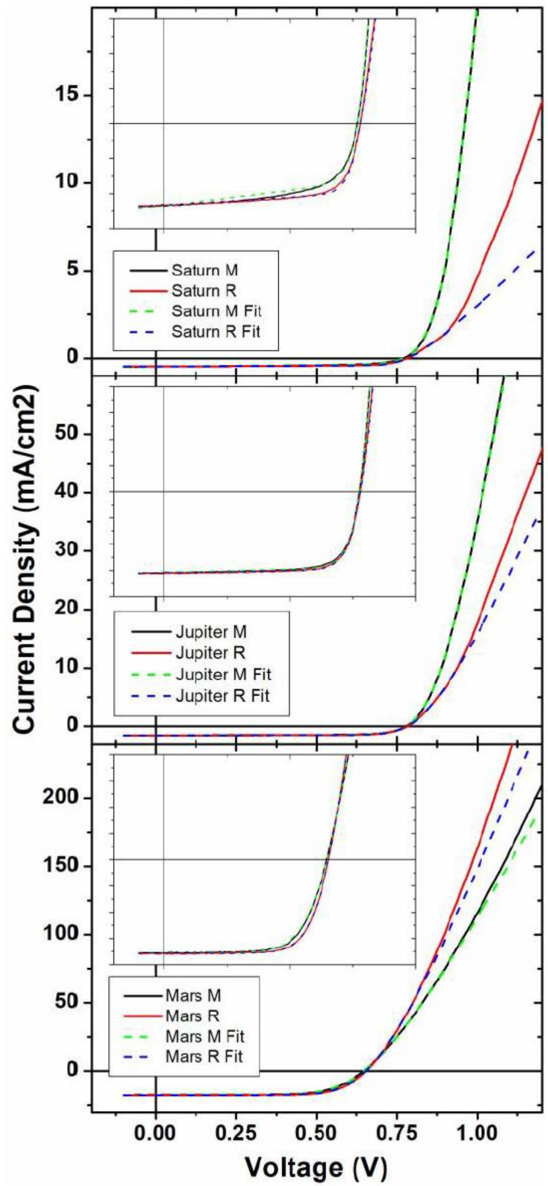


Fig. 1. Distribution of charged defects within the junction according to the Lany–Zunger model of V_{Se}–V_{Cu} divacancy [9,10].

M. Igalson *et al.*, Solar Energy Materials and Solar Cells **93** (8), 1290 (2009).



$$I = I_0\left(\exp\left(\frac{q(V-R_sI)}{nk_BT}\right)-1\right)+\frac{(V-R_sI)}{R_{sh}}-I_{ph}$$

Saturn: T = 100 K; I = 0.01 suns

- Loss of Fill factor in M-state
- Evidence of parasitic barrier

Jupiter: T = 135 K; I = 0.04 suns

- Loss of Fill factor in M-state (less than observed in Saturn)
- Higher thermal energy

Mars: T = 263 K; I = 0.4 suns

- Comparable fill factor (R and M)
- Reversal observed/ higher R_s in M-state

- Evidence of generation recombination losses in the bulk.

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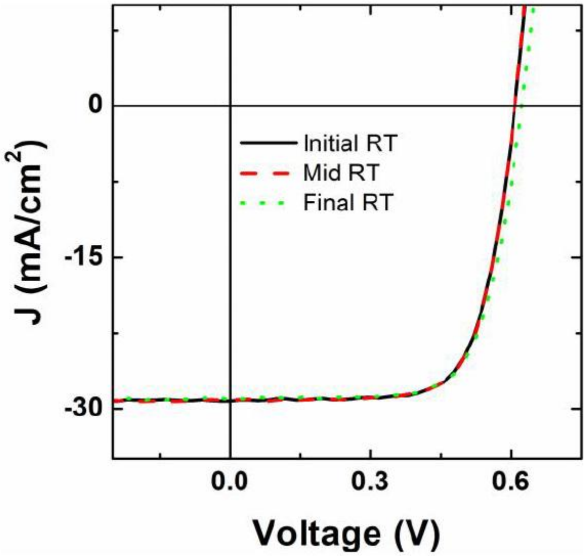
Thermal Cycling and LILT Analysis



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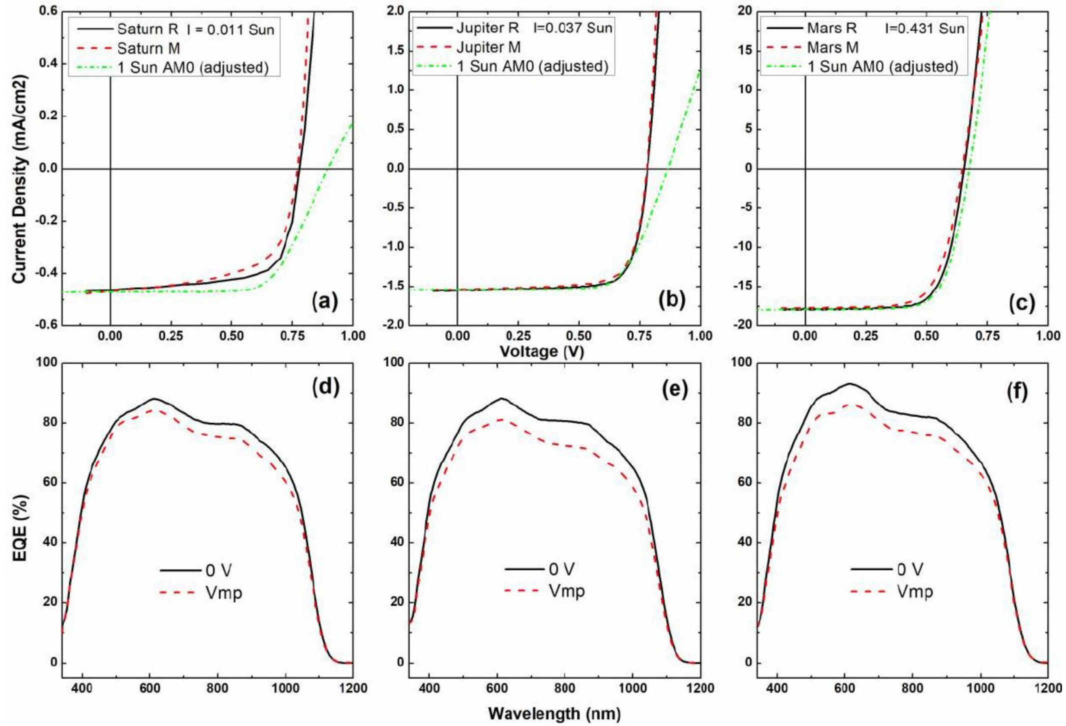
- Initial – AM1.5G 300 K
- Mid RT – after 12 hour at -100 ˚C
- Final RT – after 12 hour at 100 ˚C

No significant degradation – some improvement after high temperatures!



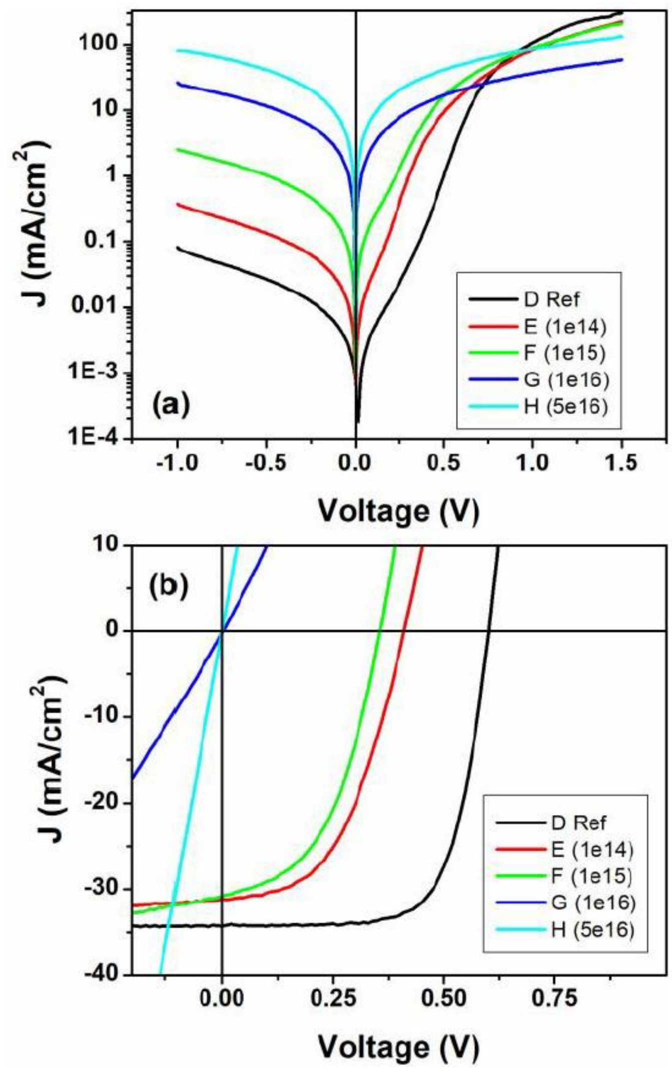
$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_l}{I_0} + 1\right)$$

- Solar Cells measured at conditions equivalent to Saturn, Jupiter, and Mars
- Loss of voltage in lower LILT conditions compared with AM0 – *metastable defects/impurities*
- Evidence of photosensitive barrier at lower temperatures
- EQE suggest losses are Voltage related

LILT EOL array specific power	8-10 W/kg

- Initial AM0 PCE ~ 13-14%
- LILT AM0 PCE ~ 19%
- LILT specific power at 19% PCE – 6.2 W/kg

Effects of proton irradiation



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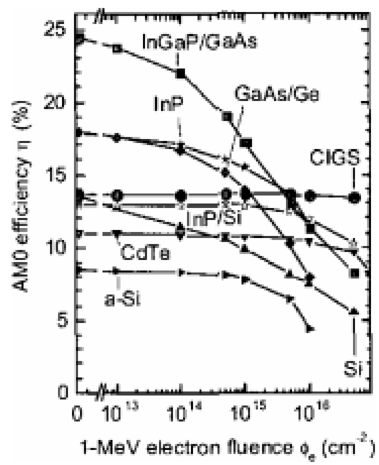
- Solar cells exposed to 1MeV proton irradiation/fluence from 1×10^{14} protons/cm^2 to 1×10^{16} protons/cm^2 – no encapsulation
- Rapid degradation evident….
- Significantly higher than typically used!



A. Jasenek *et al*., Proc. WCPEC-3, 2003.

Fluence (e^-/cm^2)	Efficiency 5AU -125°C	Efficiency 1.58AU -125°C	Efficiency 1AU 28°C
0e00 (Ctrl)	37.6% ± 0.7%	39.0% ± 0.5%	33.0% ± 0.4%
1e15 (Rad)	35.0% ± 0.6%	36.2% ± 0.7%	27.0% ± 0.4%
4e15 (Rad)	27.9% ± 0.4%	29.6% ± 0.7%	20.8% ± 0.2%

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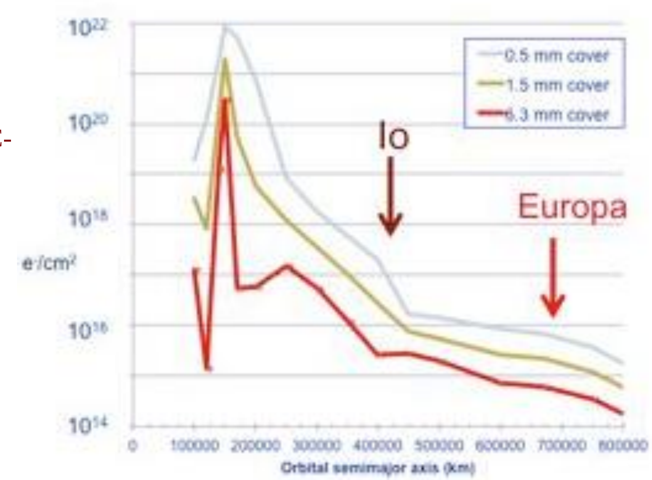
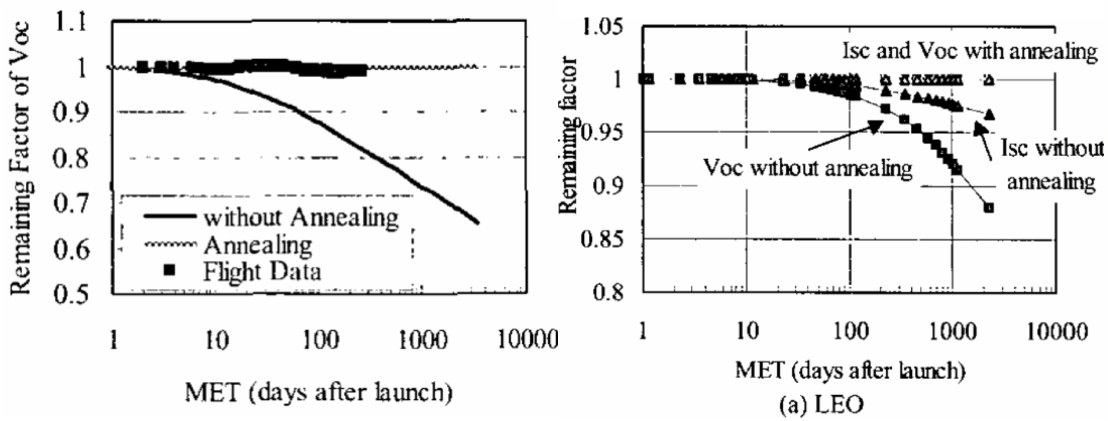
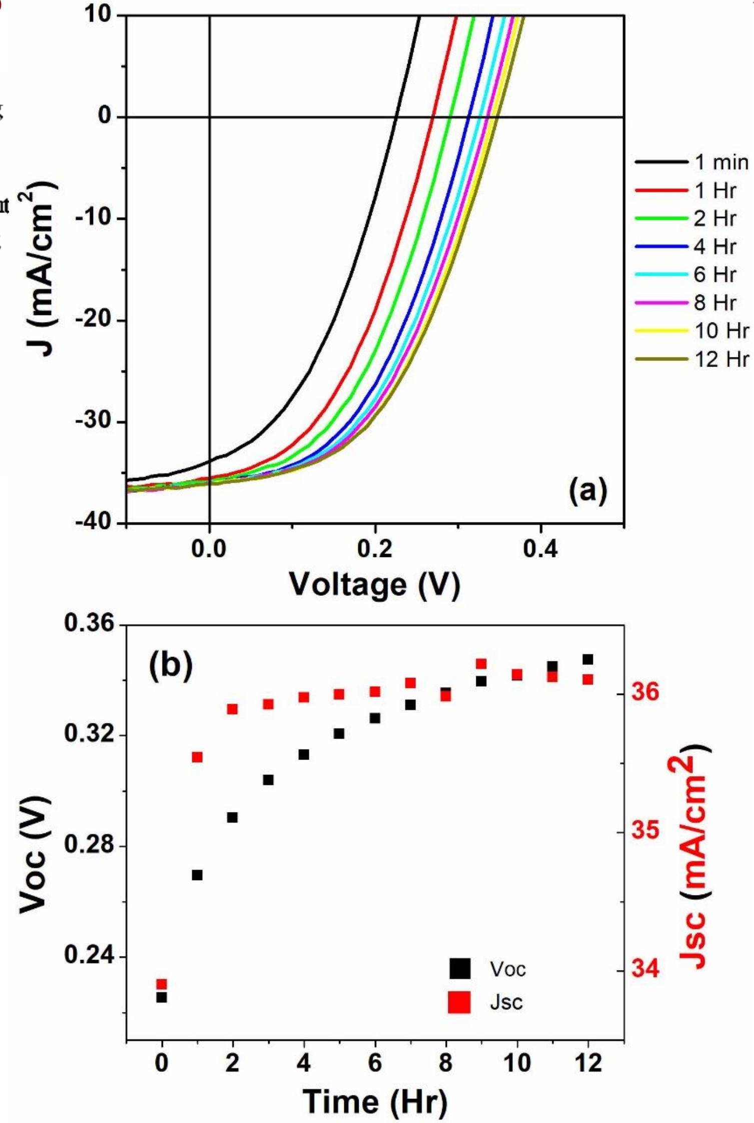


Self-Healing behavior of proton irradiated samples



Kawakita *et al*. WCPEC 2003



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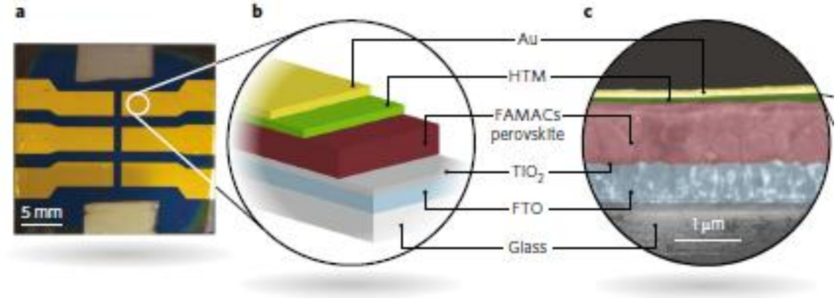
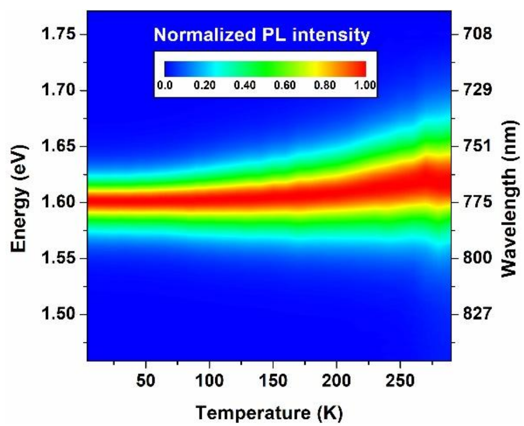
- **MDS-1 satellite showed CIGS cells healed from radiation by annealing**
- **Cells exposed to heat (100C) under AM0 illumination**
- **Upon heating strong evidence of "self-healing"**
- **Further studies underway**

LILT studies of promising thin film solar

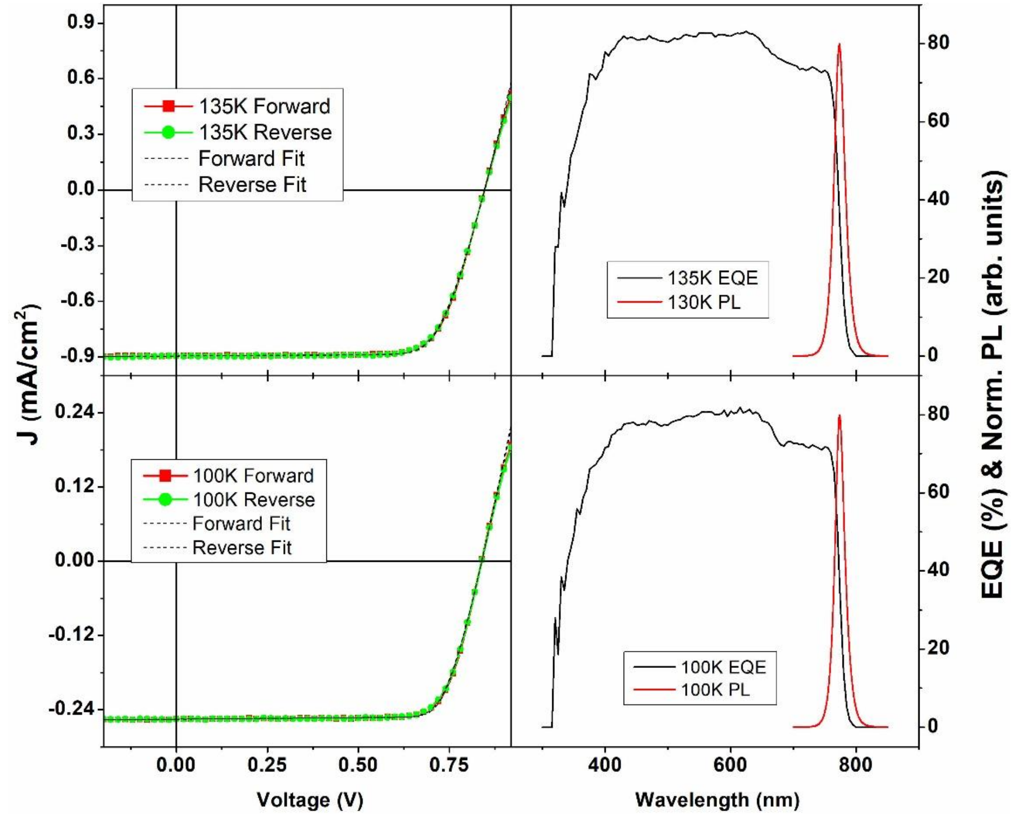


J. A. Christians *et al.*, Nature Energy **3** (1), 68 (2018).

- LILT studies of FAMACs perovskite
- High stability



- Show some promise for LILT space applications



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Credit: Giles Eperon

Summary and Acknowledgements

- **For future trips to deep space locations, technologies unique to the rigors of those environments need to be developed**

- **CIGS appear to have unique potential for deep space CubeSat and SmallSat applications**

- K. Hossain
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